VISIT…

14

Nuclear Reactors and Power Generation

Nuclear reactors fall into the following categories: zero-power research reactors, test reactors, special isotope production reactors, and power reactors. Basically, all nuclear reactors are similar in that they all utilize the fission chain reaction process to provide heat energy through the splitting (fission) of the heavy nuclei of fissionable materials. This reaction produces about 1×10^8 times the energy release of burning 1 carbon atom of fossil fuel plus the production of extra neutrons needed to sustain the chain reaction. The fuel used is generally ^{235}U (uranium-235), ^{233}U (uranium-233), or ^{239}Pu (plutonium-239). This chapter provides general information on reactors, with emphasis on those used in power generation.

I. REACTOR TYPES

The power reactor, whose main function is to furnish energy, consists broadly of a core containing nuclear fuel, a moderator (although this is eliminated in fast neutron reactors), a cooling system, a control system, and shielding. In practice, it is possible to design an almost endless number of different but basically similar reactor types by using various combinations of fuel, coolant, and moderator. It would seem that such a variety could lead to confusion, but in actuality, certain combinations are ruled out by unavailability of some of the components or by economics. For example, many areas must use natural uranium because of the lack of enrichment capabilities. This rules out certain reactors, such as the fast flux. Also, the use of natural uranium puts a limitation on the type of moderator, critical size, and power level, and although heavy water is a good moderator, especially for reactors using natural or low enrichment fuels, its cost has militated against its widespread use.

For these reasons, various countries throughout the world have pursued particular course of designs depending on the availability of materials for construction, moderator, and fuel. For example, most European nations and Canada based their first-generation reactor designs on the use of natural uranium because of a lack of enrichment facilities.

Copyright 2001 by Exxon Mobil Corporation. All Rights Reserved.

On the other hand, the United States, with its extensive system built for defense purposes, has concentrated its reactor designs on enriched fuels. Most countries using nuclear reactors currently have the ability to produce or obtain enriched fuel.

A. Basic Reactor Systems

Among the hundreds of combinations of fuel, coolant, moderator, and so on that are theoretically possible as reactor systems, six basic types have been studied in research stages and have resulted in demonstration or commercial reactors.

1. Pressurized-water reactor (PWR)
2. Boiling water reactor (BWR)
3. Sodium–graphite reactor (sometimes called light-water-cooled, graphite–moderated reactor: LGR)
4. Fast breeder reactor, including the liquid metal, fast breeder reactor (LMFBR)
5. Gas-cooled reactor (GCR)
6. High temperature, gas-cooled reactor (HTGR)

Figure 14.1 shows the schematics for each of these reactor designs, with Figure 14.1e representing both gas-cooled and high temperature gas-cooled reactors.

1. Pressurized Water Reactor

Fission heat is removed from the reactor core by water pressurized at approximately 2000 psi to prevent boiling. Steam is generated from secondary coolant in the heat exchanger. The major characteristics of this reactor are as follows.

Light water (H_2O) is the cheapest coolant and moderator.
Water is a well-documented heat transfer medium, and the cooling system is relatively simple.
High water pressure requires a costly reactor vessel and leakproof primary coolant system.
High pressure, high temperature water at rapid flow rates increases corrosion and erosion problems.
Steam is produced at relatively low temperatures and pressures (compared with fossil-fueled boilers) and may require superheating to achieve high plant efficiencies.
Containment requirements are extensive because of possible high energy release in the event of a primary coolant system failure.

2. Boiling Water Reactor

Fission heat is removed from the reactor by conversion of water to steam in the core. Such reactors have the following major characteristics.

Light water is the coolant, moderator, and heat exchange medium, as in a pressurized-water reactor.
Reactor vessel pressure is less than in the primary circuit of the pressurized reactor.
Steam pressures and temperatures are similar to those of pressurized-water reactors.
Heat exchangers, pumps, and auxiliary equipment requirements are reduced or eliminated.

Copyright 2001 by Exxon Mobil Corporation. All Rights Reserved.

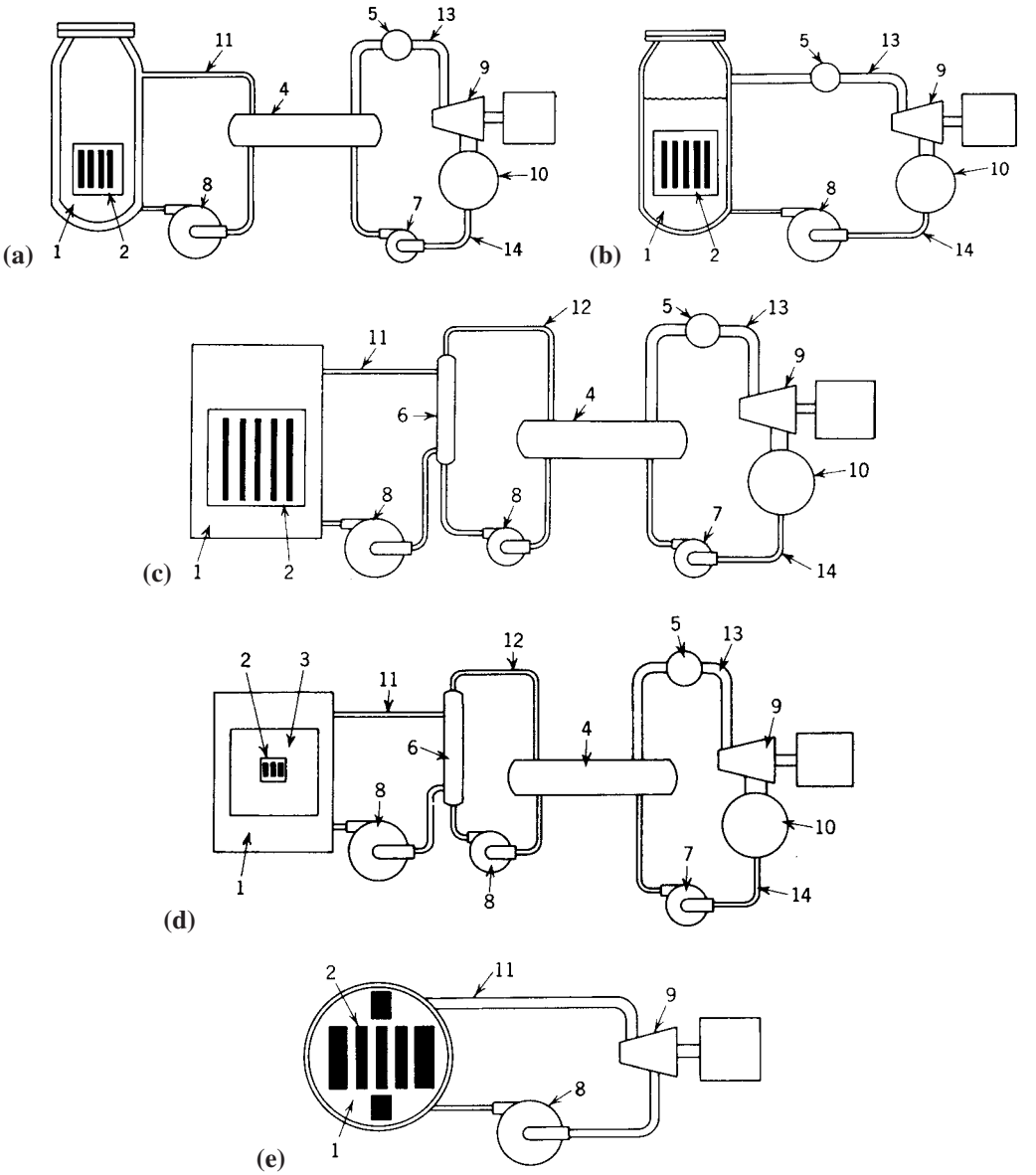

Figure 14.1 Common nuclear reactor schematics. (a) Pressurized-water reactor. (b) Boiling water reactor (direct cycle). (c) Sodium–graphite reactor. (d) Fast breeder reactor. (e) Gas-cooled and high temperature gas-cooled reactor. *Key:* 1, reactor; 2, core; 3, blanket; 4, boiler; 5, steam drier; 6, intermediate heat exchanger; 7, feed water pump; 8, circulating pump; 9, turbogenerator; 10, condenser; 11, primary coolant; 12, intermediate coolant; 13, steam 14, condensate; 15, circulating fuel.

Copyright 2001 by Exxon Mobil Corporation. All Rights Reserved.

Power surge causes a void formation, thus reducing the core power level and providing an inherent safety characteristic.

3. Sodium–Graphite Reactor

Molten sodium metal transfers high temperature heat from graphite-moderated core to an intermediate exchanger. Intermediate sodium–potassium coolant transfers heat to the final water in the boiler for steam generation. The major characteristics are as follows.

The high boiling point of liquid metal eliminates pressure on the reactor and primary systems.
High reactor temperatures are permitted.
Steam is generated at relatively high temperatures and pressures.
Corrosion problems are minimized.
Low coolant pressures reduce containment requirements.
Violent chemical reaction with water and high radioactivity of alkali metal requires a triple-cycle coolant system with dual heat exchange equipment to minimize hazards.
The core is relatively complex.

4. Fast Breeder Reactor

Heat from fission by fast neutrons is transferred by sodium coolant through an intermediate sodium cycle to steam boilers as in the sodium–graphite type. No moderator is used. Neutrons escaping from the core into a blanket breed fissionable ^{239} Pu-239 from fertile ^{238}U blanket. Fast breeder reactors have the following major characteristics.

Reactor is designed to produce more fissionable material than is consumed.
Low absorption of high energy neutrons permits wide choice of structural materials.
Low neutron absorption by fission products permits high fuel burn-up.
A small core with a minimum area intensifies heat transfer problems.
Core physics, including short neutron lifetime, makes control difficult.

5. Gas-Cooled Reactors

Heat removed from the core by gas at moderate pressure is circulated through heat exchangers that produce low and high pressure steam. Such reactors, which utilize carbon dioxide gas, graphite moderator, and natural uranium fuel, have the following major characteristics.

Utilize natural uranium fuel and relatively available materials and construction.
Permit low pressure coolant and relatively high reactor temperatures.
Containment requirements are moderate and corrosion problems minimal at low temperatures.
Reactor size is relatively large because of natural fuel and graphite moderator.
Power density (kilowatt output per liter of core volume) is extremely low.
Poor heat transfer characteristics of gases require high pumping requirements.
Steam pressures and temperatures are low.
Carbon dioxide gas is relatively cheap, safe, and easy to handle.

Copyright 2001 by Exxon Mobil Corporation. All Rights Reserved.

6. High Temperature, Gas-Cooled Reactors

Heat from the reactor core is carried by inert helium to the heat exchanger for generation of steam or directly to a gas turbine. The gas returns to the reactor in a closed cycle. These reactors have the following major characteristics.

Good efficiency can be achieved in a dual cycle with a minimum gas temperature of 1400°F (760°C).
High fuel burn-up is possible and conversion of fertile material permits lower fuel costs.
Minimum corrosion of fuel elements will be caused by inert gas.
High temperature coolant minimizes the disadvantages of poor heat transfer characteristics of the gases.
Fuel element failure may cause contamination of turbine in direct cycle.
The design of fuel elements for long life is complicated by high temperatures.
The supply of helium worldwide is limited.
Graphite is combustible.

II. RADIATION EFFECTS ON PETROLEUM PRODUCTS

In general, radiation damage may be defined as any adverse change in the physical and chemical properties of a material as a result of exposure to radiation. Radiation damage is a relative term for the changes in a material that may have adverse effects on the operation of the nuclear plant. This is true of organic materials in particular; for example, the evolution of a gaseous hydrocarbon from a liquid organic material may result in an explosion hazard and an increase in liquid viscosity. Similarly, radiation of an organic fluid may result in unwanted increase in molecular size, with consequent thickening or solidification of the liquid or grease. In the study of radiation damage, we are concerned mainly with the adverse or undesirable changes in the lubricants that affect their ability to perform adequately in the machinery involved. It should be noted that that lubricants can still perform their lubrication function after reaching levels deemed unsatisfactory for continued use by conventional laboratory evaluations. This aspect is important in applications where equipment (reactor and other containment equipment) may not be accessible until such events as fuel rod changes, set up on 18- to 24-month cycles. If analysis of these lubricants indicates undesirable changes in their characteristics, it become necessary to decide whether the lubricant can be allowed to perform until the time for a scheduled outage arrives or whether other alternatives need to be considered.

Broadly speaking, there are two mechanisms of radiolysis that must be considered in a study of the damage to organic fluids. One is the primary electronic excitation and ionization of organic molecules caused by β particles, γ rays, and fast neutrons. The other is the capture of thermal neutrons and some fast neutrons by nuclei that would cause changes in the nuclei and the generation of secondary radiation that would result in further damage.

Two methods are utilized to measure radiation energy. One measure, the quantity of energy to which the materials exposed, is called the roentgen (R); the other, the amount of energy the material absorbs, is called the rad. For γ radiation, the exposure unit (roentgen) is defined as the quantity of electromagnetic radiation that imparts 83.8 ergs of energy to 1 gram of air.

Copyright 2001 by Exxon Mobil Corporation. All Rights Reserved.

The radiation dosage of a material is defined as an absorption of 100 ergs of energy by 1 gram of material from any type of radiation. Actually, absorbed energy will vary with the type of radiation, and the effect will depend on the material exposed. For γ radiation, however, one rad absorbed is approximately equivalent to 1.2 R of radiation dosage. The rad is useful for comparing the equivalent energy of mixed radiation fluxes but does not distinguish between types.

From a radiation damage standpoint, 1 rad of neutron flux causes 10 times more biological damage to tissue than an equivalent amount of absorbed energy of γ rays. For petroleum products, however, the dosage, as measured by such effects as viscosity increase, is almost equivalent for the two types. This is discussed in more detail later in this chapter. The general levels of radiation dosage are as follows:

Dosage (Rs)	Effect
200–800	Lethal to humans
$<$5 million	Negligible to petroleum products
5–10 million	Damaging to petroleum products
$>$10 million	Survived by only most resistant organic structures

Based on experimental work, the damage to petroleum products may be summarized in the following list.

1. Liquid products (fuels and oils) darken and acquire an acrid, oxidized odor.
2. Hydrogen content decreases and density increases.
3. Gases such as hydrogen and light hydrocarbons evolve.
4. Physical properties change, higher and lower molecular weight materials are formed, and olefin content increases.
5. Viscosity and viscosity index increase.
6. Polymerization to a solid state can occur.

It must be appreciated that the intensity of these effects or the incidence of one or more of them depends on the amount of absorbed energy, the exact composition of the specific petroleum material, and other environmental conditions such as temperature, pressure, and the gaseous composition of the atmosphere.

A. Mechanism of Radiation Damage

Organic compounds and covalent materials do not normally exist in an ionized state and therefore are highly susceptible to electronic excitation and ionization as the result of deposited energy. Covalent compounds, including the common gases, liquids, and organic materials, consist of molecules that are formed by a group of atoms held together by shared electron bonding, which yields strong exchange forces. The molecules are bound together by relatively weak van der Waals forces.

Conversely, ionic compounds, such as inorganic materials, which include salts and oxides, are already ionized (metals may be considered to be in an ionized state) and are not susceptible to further electronic excitation. Ionic compounds consist of highly electropositive and electronegative ions held together in a crystal lattice by electrostatic forces in accordance with Coulomb's law. There is no actual union of ions in the crystal to form molecules, although all crystals may be considered to be composed of large molecules of a size limited only by the capacity of the crystal to grow.

Therefore, the effect of radiation energy on nonionic compounds is to form ions, radicals, and excited species and thereby make the compounds more reactive with them-

Copyright 2001 by Exxon Mobil Corporation. All Rights Reserved.

selves or with the atmospheric environment. On the other hand, the effect of radiation on ionic compounds is to change the properties of the compound related to crystal structure.

B. Chemical Changes in Irradiated Materials

The physical and chemical properties of hydrocarbon fluids that make them important as lubricants change during irradiation to varying degrees based on chemical composition and the presence of additives. These changes may be traced to alteration of the chemical structure of the materials. Nuclear irradiation, either directly or by secondary radiation, deposits high level energy in the irradiated organic substance and causes ionization and molecular excitation. The ions are excited molecules that rapidly react to form free radicals, which further combine or condense (Figure 14.2).

The changes in chemical structure may be measured by various classical methods: for example, it is possible to determine the approximate number of free radicals formed by the use of scavengers such as iodine. In addition, either hydrogen or light petroleum fractions are evolved as gas. Investigations have shown that both carbon–hydrogen and carbon–carbon bonds can be broken by radiolysis. The dissociated or ionized molecules can condense, rearrange, and form olefins or other products, depending on the environment. At temperatures below 400°F (204°C), temperature effects do not seem to be significant.

Because most petroleum lubricants contain combinations of saturated and unsaturated aliphatic and aromatic compounds, the reactions of these principal hydrocarbon classes have been studied under the influence of ionizing radiation. These studies (Table 14.1) indicate, as would be suspected, that unsaturated hydrocarbons are most reactive and aromatics the least affected. Saturated compounds fall somewhere between the two

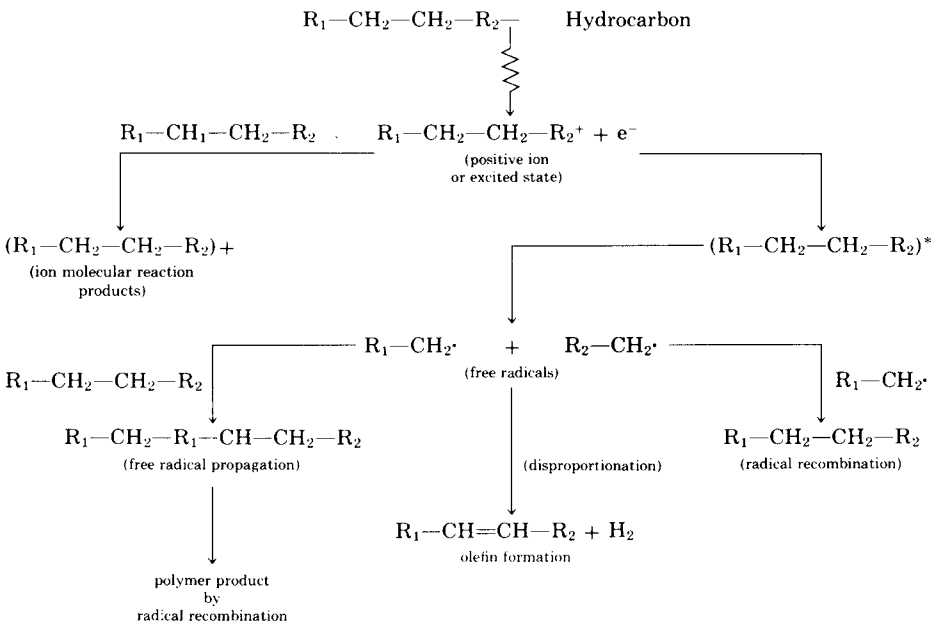

Figure 14.2 Radiolysis processes in hydrocarbons.

Copyright 2001 by Exxon Mobil Corporation. All Rights Reserved.

Table 14.1 Summary of Radiation Changes in Organic Compounds

Condition	*G* values[a]		
	Saturated hydrocarbons	Unsaturated hydrocarbons	Aromatic hydrocarbons
Polymerization	None	10–10,000	None
Cross-linking	~1	6–14	<1
H_2 evolution	2–6	1	0.04–0.4
CH_4 evolution	0.06–1	0.1–0.4	0.001–0.08
Destruction of irradiated material	4–9	6–2000	<1

[a] G = molecules produced, destroyed, or reacted per 100 eV of energy absorbed
Source: Nuclear Engineering Handbook. Used by permission of McGraw-Hill Book Co., Inc.

extremes. The results are expressed as G values: that is, the number of molecules reacting or produced for each 100 eV of ionizing radiation. For example, at least 6–14 molecules of unsaturated hydrocarbons react for each 100 eV. In certain instances, high G values (up to 10,000) result for free radical polymerization, whereas low G values ($G = 6$) are formed for random cross-linking, and very low values ($G < 1$) for methane formation.

Aromatic materials, with a G value for destruction of 1, are highest in radiation resistance. The principal reaction is cross-linking, from which very small amounts of gas evolve.

Additional studies were made on a range of petroleum oils representative of typical paraffinic, naphthenic, and aromatic materials varying in sulfur content. The viscosity was plotted against aromatic and sulfur content (Figure 14.3). The data show that as the aromatic content increases, the viscosity increase is reduced almost linearly. The effect of sulfur content is similar but more marked. Further, it was noted that radiation damage appears greatest for oils with the highest molecular weights or the highest initial viscosity.

Because it was found that naturally occurring compounds improved the radiation stability of petroleum oils and that these compounds were usually removed by refining procedures, the effect of using synthetic aromatic and sulfur as additives was studied. From these studies, it appears that a disulfide, or an alkyl selenide, provides good protection against radiation damage. The disulfides prevent polymerization by a mechanism termed free radical chain stopping. The disulfides have an advantage also of being good EP and antiwear agents but do not prevent oxidation or olefin formation.

It is well known, however, that aromatic compounds possess good thermal and radiation stability and in the latter case protect less stable aliphatic molecules by the transfer of energy. These compounds are usually characterized by complex molecules that resonate between a number of possible electronic structures and, therefore, possess fairly stable excited energy states. In other words, when a paraffinic hydrocarbon absorbs energy, it is raised to an unstable state in which the energy is greater than the electronic forces that constitute the chemical bonds. The result is a bond fracture with residual free radicals. In an aromatic with an equivalent absorbed energy, the higher level is not sufficient to sever the greater electronic binding forces, and the energy is eventually liberated as heat or light. The aromatic petroleum extracts exhibit radiation stability as follows, in decreasing order: polyglycols, paraffinic hydrocarbons, diesters, and silicones. Aromatic compounds

Copyright 2001 by Exxon Mobil Corporation. All Rights Reserved.

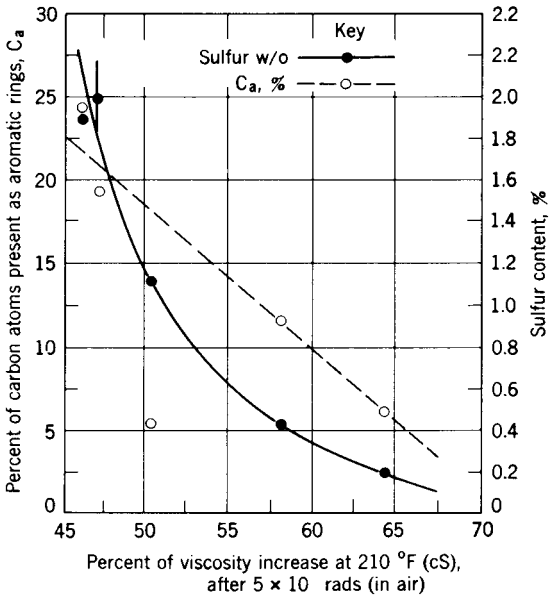

Figure 14.3 Radiation stability versus sulfur and aromatic content.

were studied to determine their effects both as pure synthetic fluids and as antiradiation additives to mineral oils. The results, given in Figures 14.4 and 14.5, show the following relationships.

1. The aromatics with bridging methylene groups between aromatic molecules are less efficient as protective agents than antiradiation additives with direct links between aromatic rings.
2. Long chain alkyl groups attached to the aromatic rings make less effective protective agents, probably because of a difference in stability of the compound and a lowering of the aromatic ring content.
3. Small amounts of a free radical inhibitor in addition to the aromatic additive substantially reduce the viscosity increase.
4. The protection afforded is not simply a direct function of aromatic content; in fact, it would appear that 40% of added aromatic material is a practical maximum. Beyond 40%, it is preferable to use a pure aromatic of suitable physical characteristics.

A study of the changes in properties and performance of conventional lube oils after irradiation shows the following.

1. Conventional antioxidant additives of the phenolic or amine type confer little radiation stability to base oils and are preferentially destroyed between 10^8 and 5×10^8 rads.
2. Didodecyl selenide, which is known to be an effective antioxidant, also has radiation-protective properties. The oxidation stability is effective after an irradiation of 10^9 rads.

Copyright 2001 by Exxon Mobil Corporation. All Rights Reserved.

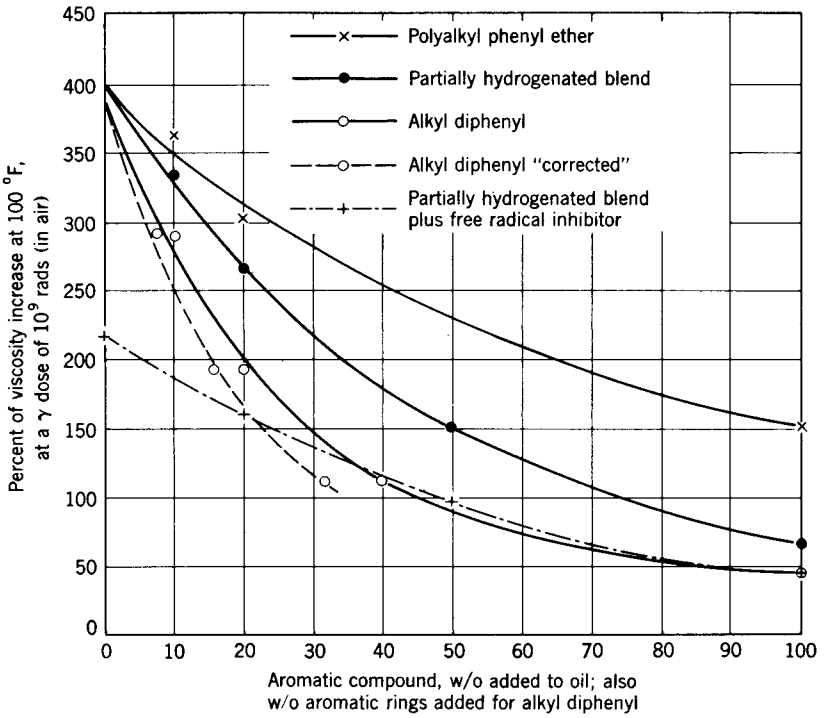

Figure 14.4 Radiation protection of synthetic aromatic additives.

3. Diester-based oils, phosphate esters (antiwear additives), and halogenated EP agents produce acids at a low radiation dose.
4. Polymers such as polybutenes and polymethacrylates cleave readily and thus lose their effect as VI improvers.
5. Silicone antifoam agents are destroyed at low radiation dose.
6. In most cases, the presence of air, compared with an inert atmosphere, increases radiation damage by a factor of 1.6–2.3 times, as indicated by viscosity increase.

In summary, high quality, conventional lubricating oils are suitable for radiation doses up to 10^8 rads. It should be noted that base oils that undergo severe hydrotreating or hydrocracking processes during refining may need to have sulfur- or aromatic-containing additives supplied to the finished product. These refining processes remove much of the content of sulfur and aromatic compounds. Further radiation resistance can be formulated into a good quality petroleum oil by use of antiradiation agents such as radical scavengers or aromatic structures. These formulated oils will protect up to exposures of 10^9 rads. Above these doses and at high temperatures, synthetic-type lubricants that use partially hydrogenated aromatics blended with aromatic polymers are required. The effect of temperature at high radiation dose (10^9 rads) has been studied under a nitrogen atmosphere for these fluids (Figure 14.5).

If, however, materials are to be satisfactory as lubricants, not only must they have good thermal and irradiation stability, but their wear characteristics must be satisfactory.

Copyright 2001 by Exxon Mobil Corporation. All Rights Reserved.

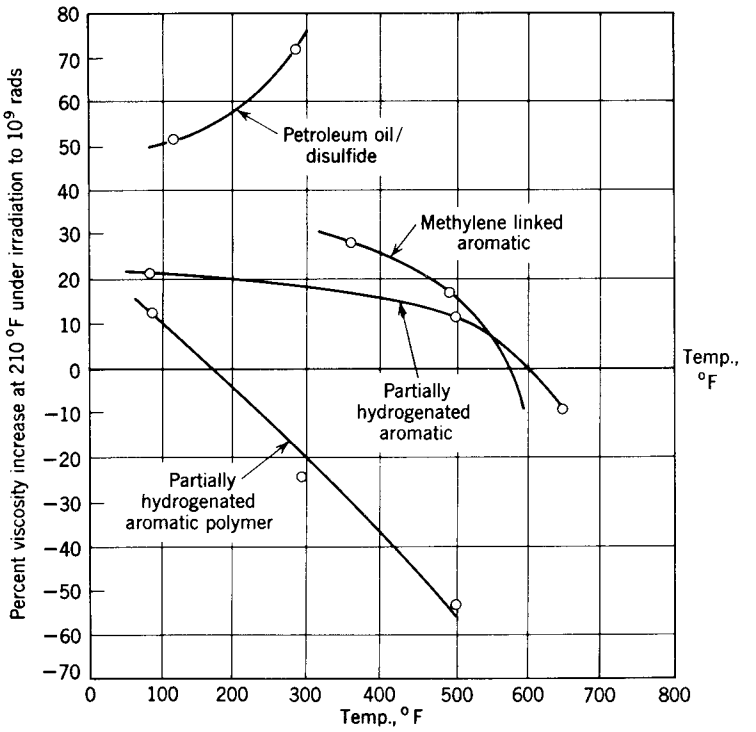

Figure 14.5 Radiation stability versus temperature; materials were studied under a nitrogen atmosphere.

This phase can use conventional laboratory and field testing for new lubricants. Additional special testing is also required to verify that the irradiated lubricants retain sufficient antiwear properties to protect the equipment over the expected service intervals.

1. Grease Irradiation

The damage caused by high energy radiation on greases is twofold. First, the radiation attacks the thickening structure and causes separation and fluidity. Following this, continued irradiation results in polymerization of the base oil, resulting in thickening and gradual solidification. The precise pattern of change is dependent on the type of thickener, the gel structure, and the radiation stability of the thickener and the base oil.

In general, greases have been evaluated for radiation damage by determining the worked penetration, following irradiation, and comparing it with the original value. These irradiation evaluations are usually of the static type, but testing under dynamic conditions during irradiation has yielded markedly different results. Typical greases that have organic soap components of alkali earth metals, although resistant to high amounts of radiation, break down at total doses of approximately 10^8 rads. Micrographs of soap structure showed a drastic change in the normal fiber structure of the gelling agent. On the other hand, greases made with nonsoap thickeners, such as carbon black, were less affected. Micrographs of a carbon black grease showed the same structure (agglomeration of carbon particles dispersed throughout the oil phase) both before and after irradiation.

Copyright 2001 by Exxon Mobil Corporation. All Rights Reserved.

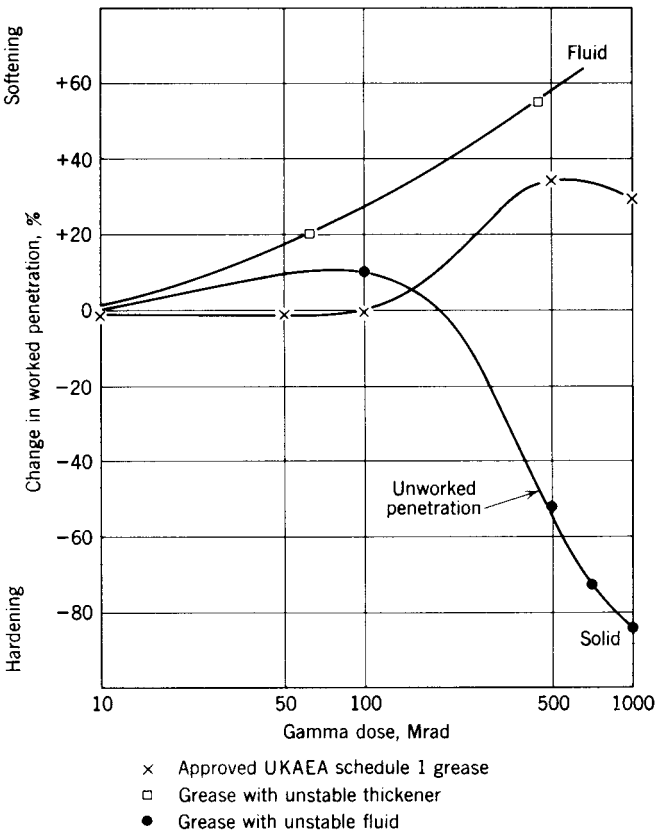

Figure 14.6 Effect of radiation on greases.

The stabilization of the thickening structure under irradiation solves the problem of softening or bleeding of the base oil but will not prevent the eventual solidification of the grease. This is a function of the base oil, and the solutions discussed in connection with lubricating oil (use of antiradiation additives or synthetic organics as base fluids) are valid.

The mechanism of change for three greases is shown in Figure 14.6. In one case, the grease had an unstable thickener and progressively softened to fluidity. Although such a grease might protect a bearing, the problem of leakage would be great, and incompatibility with reactor components would be a concern. The second grease gradually decreased in penetration (solidification) after an initial increase or softening. Such a grease would cause failure in the lubricated mechanism. The third grease showed good stability with a slight softening up to 10^9 rads.

2. Radiation Stability of Thickeners

The selection of the thickener or solid phase of a grease designed for nuclear applications requires consideration of compatibility as well as resistance to radiation, high temperatures, mechanical shear, and operating atmosphere.

Copyright 2001 by Exxon Mobil Corporation. All Rights Reserved.

Table 14.2 Elements on Which the UKAEA Places Restrictions[a] Are for Radiation-Resistant Lubricants Used in Reactors Employing Magnox Fuel Cans

None allowed	Mercury
0.1% allowed	Barium, bismuth, cadmium, gallium, indium, lead, lithium, sodium, thallium, tin, zinc
1% allowed	Aluminum, antimony, calcium, cerium, copper, nickel, praseodymium, silver, strontium

[a] These limits can be exceeded where it can be shown that the metals are present in stable compounded form and that practical compatibility tests are satisfied.

Certain elements are unsuitable because their presence within or close to the reactor core could seriously affect neutron economy or react with the fuel element cladding to cause destruction and possible release of fission products. Accordingly, the United Kingdom Atomic Energy Authority (UKAEA) has restricted lubricant composition (Table 14.2).

The effect of atmosphere can be illustrated by air, which has a serious oxidizing effect, especially when coupled with radiation and high temperatures. Conventional antioxidants are destroyed as noted earlier. Some of the organic-modified thickeners have an antioxidant effect and perform dual functions. Hot pressurized carbon dioxide can cause rapid degeneration of conventional soap-thickened greases, presumably by means of carbonate formation.

In selection of a thickener, the compatibility of the thickener and base fluid is of paramount importance. Even an exceptionally radiation-resistant thickener, when in combination with certain base fluids, may at best yield weak gels and soften easily. For example, a satisfactory grease structure is extremely difficult to obtain when an Indanthrene pigment is used with a paraffinic bright stock.

Various nonsoap thickeners that form good grease structure with both mineral oil and synthetic fluid bases are available. These thickeners may be grouped as follows.

1. *Modified clays and silicas.* Typical of the modified clays are Bentone and Baragel, which are formed by a cation exchange reaction between a montmorillonite clay and a quatenary ammonium salt. This reaction produces a hydrocarbon layer on the surface of the clay, which makes it oleophilic. Finely divided silicas may be treated with silicone to render them hydrophobic, or, as with Estersil, the silica may be esterified with *n*-butyl alcohol.
2. *Dye pigments.* Organic toners or dye pigments are utilized as grease thickeners (e.g., Indanthrene).
3. *Organic thickeners.* Typical of this type are the substituted aryl ureas characterized by the diamide–carbonyl linkage, which may be formed in situ by the reaction of diisocyanate with an aryl amine.

The behavior of these thickeners, when used in conjunction with a synthetic fluid, is shown in Figure 14.7.

As with fluid lubricants, antiradiation compounds may be added to the grease to increase its radiation stability.

Copyright 2001 by Exxon Mobil Corporation. All Rights Reserved.

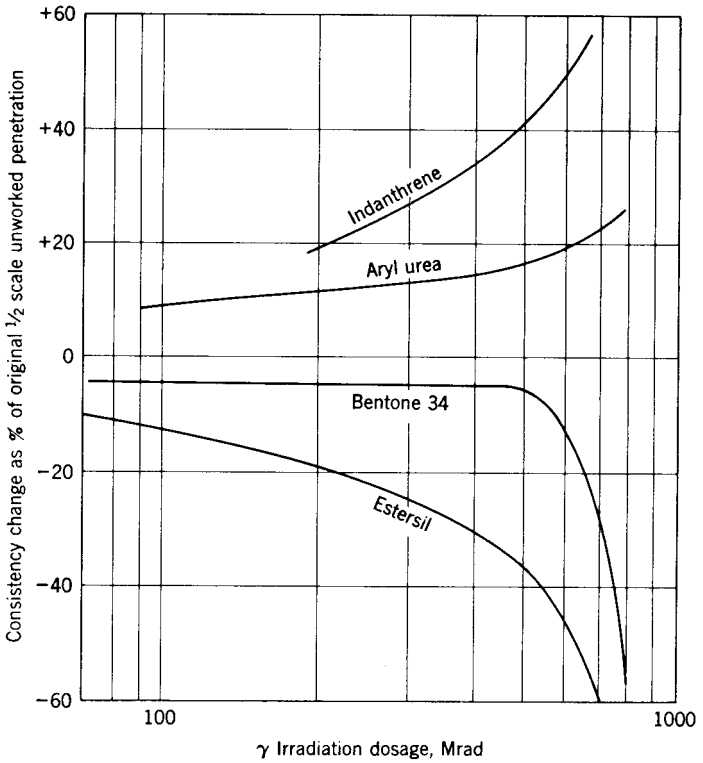

Figure 14.7 Effect of thickener on grease polymerization.

III. LUBRICATION RECOMMENDATIONS

The advent of nuclear energy has added a new dimension to the requirements of lubricants and other petroleum products in industrial applications. All equipment used in the nuclear industry—research and power reactors; fuel processing machinery; conveyors, manipulators, and cranes in irradiation facilities; viewing windows and shield doors in hot cells; heat exchange units—requires oils, greases, and other organic fluids to perform conventional and special functions in an irradiated atmosphere.

Nowhere are the operating conditions of radiation, temperature, and atmosphere more damaging than in a power reactor field. At the outset, equipment was designed to operate without conventional petroleum lubricants because little was known of the behavior of petroleum products under irradiation; moreover, the exact severity of the application was overestimated. This placed a design and economic burden on nuclear power generation. As experience was gained in the operation of these plants, the original position was reconsidered. First, specific operating parameters of radiation flux, temperature and so on, were obtained, which realistically established the requirements. Then research into the radiation resistance of petroleum materials showed that conventional lubricants can withstand doses up to 10^7–10^8 rads and still perform their lubrication function. New specialized lubricants were developed to withstand more than 10^9 rads. As a consequence of this knowledge

Copyright 2001 by Exxon Mobil Corporation. All Rights Reserved.

and experience, proved engineering designs employing conventional petroleum greases and lubricating fluids have been adopted since the late 1950s.

Because the nuclear power industry is so complex and is under continuous scrutiny, patterns of design and operating conditions are changing. In addition, most equipment is unique, and each plant requires separate consideration before proper lubricants and lubrication schedules can be established. Little repetitiveness exists in equipment, especially in the reactor area, and in components associated with safety issues. Therefore, the best that can be accomplished in this chapter on lubrication recommendations is to furnish the background experience and establish guidelines so that lubrication engineers can, after a survey of the specific conditions, recommend the best lubricants for a particular application.

A. General Requirements

All lubrication engineers are familiar with the effect of factors such as speed, load, temperature, and time on the life of bearings and gears, and on the physical and chemical properties of oils and greases exposed to these environmental conditions.

In conventional applications, the effect of speed, load, and temperature are evaluated in making recommendations. Selecting the correct lubricant and service interval is determined by evaluating the lubricant's anticipated performance under the most critical of these conditions. For example, speed may be the determining factor with antifriction bearings, and the proper grease must resist excessive softening for the service period. In highly loaded applications, antiwear or extreme pressure properties may be the determining consideration. In most cases, however, temperature is the most critical factor. Operating severity may be determined by the degree of heat and the extent of exposure. The additional factor of radiation in nuclear applications affects lubricants in much the same manner as heat. Both are modes of energy and, as we saw earlier, lubricants, like all organic materials, undergo major structural changes when certain thresholds of absorbed energy are reached. We know that petroleum products undergo thermal cracking and polymerization at certain temperatures and, likewise, that cleavage and cross-linking occur at certain radiation dosage thresholds.

In nuclear applications, radiation energy is expressed as flux or dose rate. The particular type of radiation and the units have already been discussed. It is sufficient to state here that this dose rate, if applied over a specified interval, will yield the absorbed dose for an exposed material. If, for example, a grease can absorb a dose of 5×10^9 rads before suffering physical or chemical changes that will render it useless as a lubricant, this grease can be used for 5000 days if the dose rate is absorbed at a rate of 1 Mrad per day or for only 5 days if the dose rate absorbed is 1000 Mrad per day. As stated earlier, other factors such as temperature and atmosphere will increase or decrease these intervals.

B. Selection of Lubricants

Much has been published and extensive studies have been made that lead to the recommendations of correct lubricants. In this final analysis, however, the selection of the proper lubricant and its application to any particular equipment must be made by a lubrication engineer for each specific instance, based on operating conditions and the type of unit (bearing, gear, cylinder) requiring lubrication. Nowhere is this more pertinent than in the lubrication of the equipment in the reactor and containment areas of the nuclear power plant. Because of the uniqueness of the designs and the severity of the operating environ-

Copyright 2001 by Exxon Mobil Corporation. All Rights Reserved.

ment, each plant can be markedly different. Therefore the experience of the lubrication engineer is important, and blanket recommendations serve only as guidelines. The accumulated experience of lubrication engineers and equipment manufacturers has been helpful in numerous plants in the solution of lubrication problems and, in many cases, in the elimination of mechanical problems as well.

In selecting lubricants for a nuclear power plant, the engineer consulted in the design phases should be cognizant of development work at equipment manufacturers and should participate in practical evaluations of prototype units under the operating conditions. In surveying plant requirements, particular attention must be paid to the radiation flux profile that has been calculated for the various parts of the plant and compared with actual surveys during operation of similar plants. Some of this information is available in the form of a design basis event (DBE) developed for each plant. Extreme conservatism has been the rule in estimations of nuclear power plant requirements, often to the detriment of practical solutions.

Copyright 2001 by Exxon Mobil Corporation. All Rights Reserved.